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Opposed-Flow Flame Spread in a Narrow Channel Apparatus over Thin PMMA Sheets

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Flame spread tests have been conducted over polymethylmethacrylate (PMMA) samples in San Diego State University's Narrow Channel Apparatus (SDSU NCA). The Narrow Channel Apparatus (NCA) has the ability to suppress buoyant flow in horizontally spreading flames, and is currently being investigated as a possible replacement or complement to NASA's current material flammability test standard for non-metallic solids, NASA-STD-(I)-6001B Test 1. The buoyant suppression achieved with a NCA allows for tests to be conducted in a simulated microgravity atmosphere—a characteristic that Test 1 lacks since flames present in Test 1 are buoyantly driven. The SDSU NCA allows for flame spread tests to be conducted with varying opposed flow oxidizer velocities, oxygen percent by volume, and total pressure. Also, since the test sample is placed symmetrically between two confining plates so that there is a gap above and below the sample, this gap can be adjusted. This gap height adjustment allows for a compromise between heat loss from the flame to the confining boundaries and buoyancy suppression achieved by those boundaries. This article explores the effect gap height has on the flame spread rate for 75 μm thick PMMA at 1 atm pressure and 21% oxygen concentration by volume in the SDSU NCA.

Flame spread results from the SDSU NCA for thin cellulose fuels have previously been compared to results from tests in actual microgravity at various test conditions with the same sample materials and were found to be in good agreement. This article also presents results from the SDSU NCA for PMMA at 1 atm pressure, opposed oxidizer velocity ranging from 3 to 35 cm/s, oxygen concentration by volume at 21%, 30 %, and 50% and fuel thicknesses of 50 and 75 μm . These results are compared to results obtained in actual microgravity for PMMA obtained at the 4.5s drop tower of MGLAB in Gifu, Japan, and the 5.2s drop tower at NASA's Zero-Gravity Research Facility in Cleveland, OH. This comparison confirms that at 1 atm pressure, the SDSU NCA successfully simulates microgravity for not only thin cellulose fuels, but also for thin PMMA sheets as well. This further supports the idea that the NCA is a viable option to complement or replace NASA's Test 1 for material flammability testing. Tests with thick fuels will be conducted in the future to further characterize the SDSU NCA.

1. Introduction

The Narrow Channel Apparatus (NCA) is being studied as a possible replacement for or complement to NASA-STD-(I)-6001B Test 1, NASA's current test method used to conduct material flammability tests on non-metallic materials to be used onboard spacecraft [3]. Since Test 1 is an upward flame propagation test conducted in normal gravity, buoyancy effects play a large role in the flame behavior. These effects cause the flammability tests to be conservative in their determination of whether a particular material (at a given thickness) can be used in spacecraft or not. The SDSU NCA has the ability to more appropriately simulate actual spacecraft ventilation conditions by effectively suppressing buoyant effects and allowing the opposed flow oxidizer velocity to be controlled [7]. Buoyant effects are suppressed in the NCA by spatially confining the flow with the top and bottom plates of the channel. The test sample is placed symmetrically between two confining plates so that there is an adjustable gap above and below the sample. This gap height adjustment

allows for a compromise between heat loss from the flame to the confining boundaries and buoyancy suppression achieved by those boundaries.

Flame spread results from the SDSU NCA for thin cellulose fuels have previously been compared to results from tests in actual microgravity at various test conditions with the same sample materials and were found to be in good agreement [4,6]. This article presents results from the SDSU NCA for clear, extruded polymethylmethacrylate (PMMA) at 1 atm pressure, opposed oxidizer velocity ranging from 3 to 35 cm/s, oxygen concentration by volume at 21%, 30 %, and 50%, and fuel thicknesses of 50 and 75 μm . These results are compared to results from actual microgravity test results for thin PMMA obtained at the 4.5s drop tower of MGLAB in Gifu, Japan, and the 5.2s drop tower at NASA's Zero-Gravity Research Facility in Cleveland, OH [9, 5]. Similar to the work done on cellulose in [8], this article explores the effect gap height has on the flame spread rate for 75 μm PMMA at 1 atm pressure and 21% oxygen concentration by volume in the SDSU NCA. Gap height tests were conducted with an opposed oxidizer velocity ranging from 7 to 35 cm/s.

2. Experimental Apparatus and Procedure

The SDSU Narrow Channel Apparatus is an 8.3 cm wide by 100 cm long (in the flow direction) duct with an adjustable gap height from 1 to 25 mm (see Figure 1). Alicat MC-50SLPM-D and MC-1SLPM-D mass flow controllers are sent commands to control the oxidizer flow velocity and oxygen concentration by a remote computer with the use of a graphical user interface (GUI) created in IGOR Pro (see Figure 2). Each gas has a dedicated 50 SLPM and 1 SLPM mass flow controller, allowing calculations done in the GUI to control the flow over the desired range. Honeycomb flow straighteners are placed at the inlet and outlet to ensure uniform flow conditions and minimize flow disturbances.

The sample is overlapped with and taped to a stainless steel sample holder with a 5 cm x 30 cm cutout to match the sample size used in NASA Test 1. Care is taken to keep the sample taut. The sample holder then holds the sample in the center of the channel as shown in Figure 1. A Kanthal igniter wire with a small piece of paper around it is used to ignite the PMMA. Without the paper, the wire can slice through the PMMA without igniting it.

Tests presented in this paper, other than in the gap height comparison, have a total gap height of 10 mm. The sample is placed directly in the middle of the gap, providing an equal gap above and below the sample. This leads to a gap of 5 mm from top quartz window in the lid, and 5 mm from the aluminum bottom of the duct.

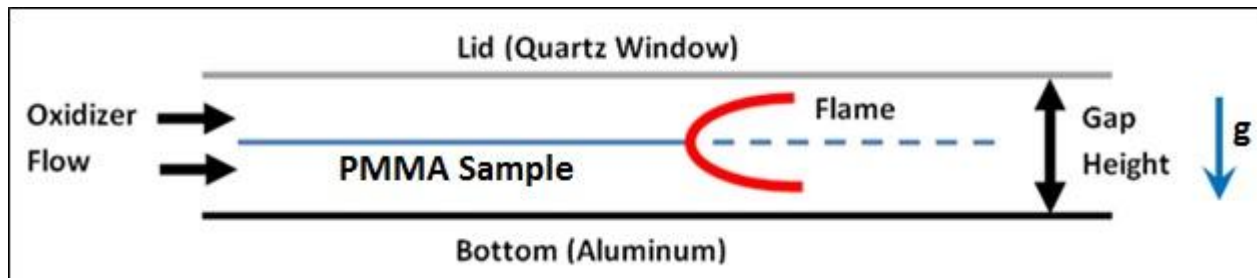


Figure 1: Side view of the SDSU NCA. Note that the sample is placed with equal spacing from the top window and bottom plate.

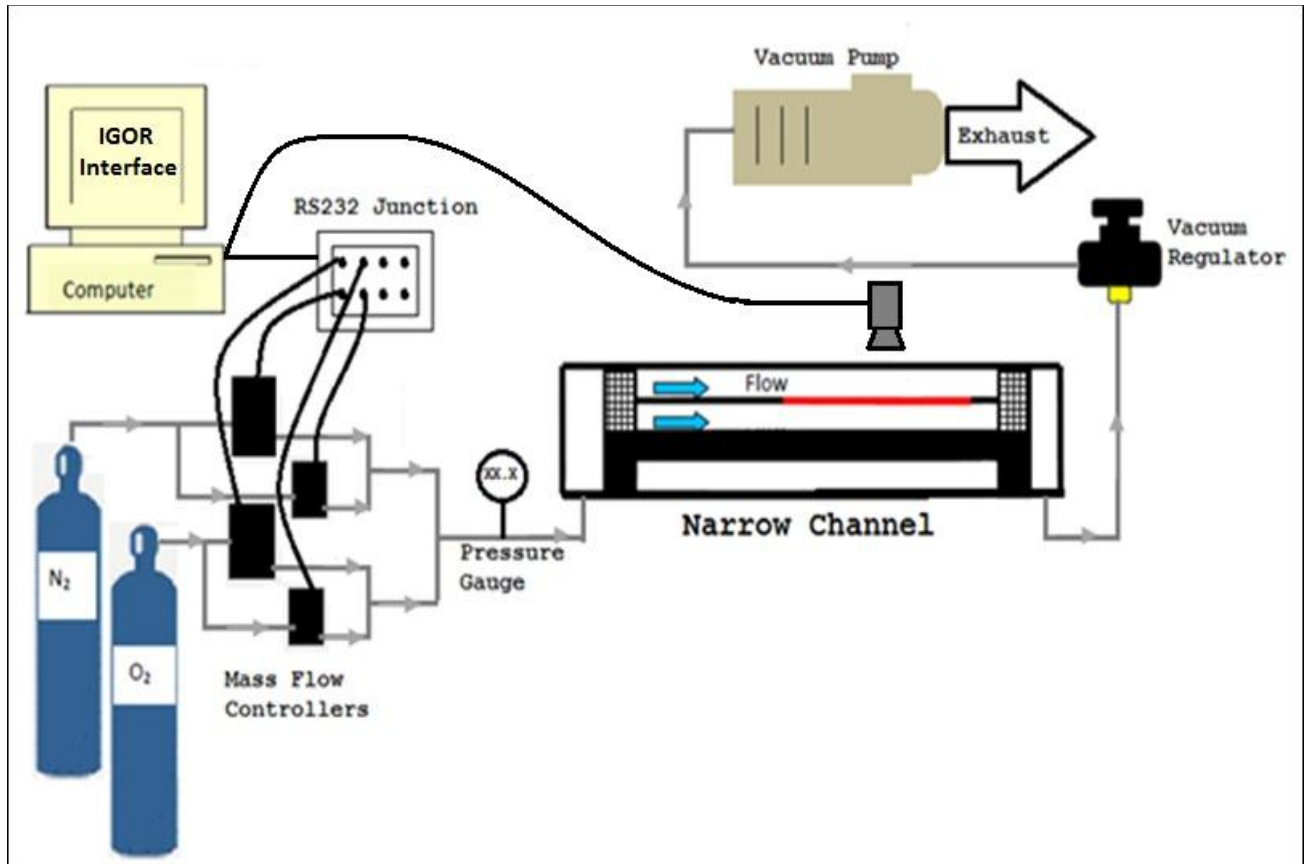


Figure 2: Schematic of the SDSU Narrow Channel Apparatus. Note the vacuum regulator and pump are not used in these tests, since all tests were conducted at atmospheric pressure.

3. Results and Discussion

The leading edge of the flame is tracked using Spotlight-16 Software [2]. The software automatically tracks the flame through the AOI by following a user-defined intensity along a straight line. The program outputs data in the form of position vs. time. This data is then copied into Microsoft Excel and plotted. Figure 3 shows an example of this plotted data for a sample of thin PMMA. Results in Figure 3 are from a test on 75 μm PMMA at 1 atm pressure, 10 mm gap height, 7 cm/s opposed oxidizer velocity, and 21 percent oxygen concentration. It is noticeable that the flame spread follows a characteristic linear position vs. time relationship, allowing for a linear curve fit of the data. In Figure 3 this leads to a flame spread rate of 0.216 cm/s, with an R-squared correlation coefficient of 0.9995.

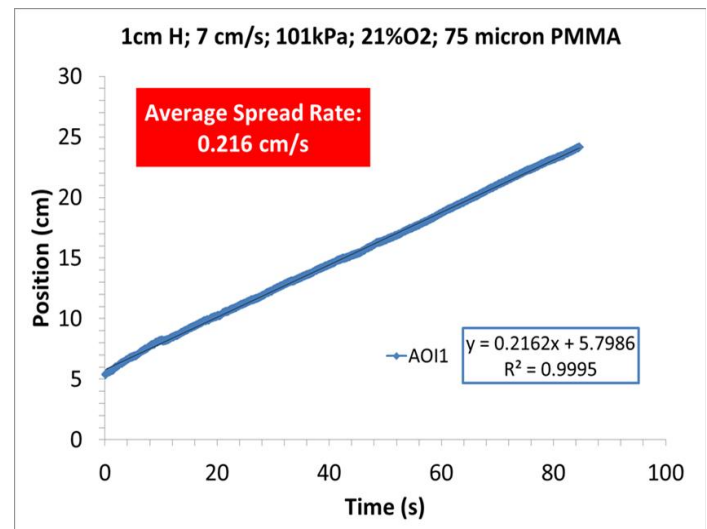


Figure 3: Example position vs. time plot

3.1 Effect of Flow Velocity and Oxygen Concentration

Figure 4 shows the flame spread rate as a function of the relative velocity between the flame and the opposed flow. For an opposed oxidizer flow, the relative velocity is the opposed flow velocity plus the flame spread rate. Tests conducted with fuel thicknesses other than 75 μm were normalized to better compare the data. Normalization was achieved using a simple thickness ratio as follows:

$$V_{f,n} = V_f \frac{t_f}{t_n}$$

Where, $V_{f,n}$ is the normalized flame spread rate, V_f is the actual flame spread rate, t_f is the fuel thickness, and t_n is 75 μm (the thickness to which all other fuels are normalized). This is based on the idea that for a thermally thin fuel the flame spread rate is inversely proportional to fuel thickness.

Flame spread results for a total gap height of 10 mm are compared to those of [5] and [9]. In [9] an equivalent flow velocity (V_{eqv}) was defined in order to correct for boundary layer development. Equations were taken from [1] because of inaccuracy in [9]. The equivalent flow velocity is therefore defined as:

$$V_{\text{eqv}} = \lambda_{\text{hyd}} V_g$$

Where λ_{hyd} is the hydrodynamic coefficient and V_g is the opposed oxidizer velocity. While a range of values (average 0.28) for the hydrodynamic coefficient were used in [9], a single value of 1/3 is used for comparisons within this work, as in [5].

In Figure 4 we can see good overall agreement between the data sets. Normalization for fuel thickness seems to collapse the data fairly well except for a few of the thickest 125 μm data points at 30 % oxygen and a single 50 μm data point at 21 %. Where there is overlap between true microgravity (open symbols) and NCA data (filled symbols) there is generally very good agreement. The NCA data also agree well with the one NASA microgravity test at 30% oxygen and 30 cm/s relative velocity. The one area on the graph where there is not such good agreement is at the very low end of the relative velocity scale where the flames extinguish. The NCA flames suffer more heat loss due to the proximity of the quartz window and the bottom plate, so that those flames tend to go out sooner than the true microgravity flames which do not have this loss mechanism.

The effects of oxygen concentration can be seen throughout Figure 4. At 21 percent oxygen concentration it is noticed that the flame spread rate raises, plateaus, and then begins to drop once again, so that there is an optimal relative velocity that maximizes the flame spread rate. As oxygen concentration is raised to 30 percent it is noticeable that the drop immediately following the plateau no longer exists within the velocities tested here. At 50 percent oxygen there is a short plateau, followed by a second raise in the flame spread rate. Further, the oxygen concentration plays a large role in the flame spread rate. The data shown have a correlation between a linear and square dependence.

During testing it was noticed that the non-charring PMMA would melt and bubble as it was burned. Afterward some of the melted PMMA would be left, unburned on the bottom plate of the narrow channel apparatus. This could possibly cause a change in the flame spread rate. Other noticeable effects during the burning process consist of changes in brightness, color, and length of the flame in the flow direction as shown in Figure 5. At lower opposed flows and during the 21 percent oxygen drop, after the plateau, the flame became less yellow and turned bluer in color. It would also shrink in length and brightness. As with opposed flow velocity, the oxygen percentage caused the same effects. The higher oxygen percentages caused brighter, yellow, and longer flames.

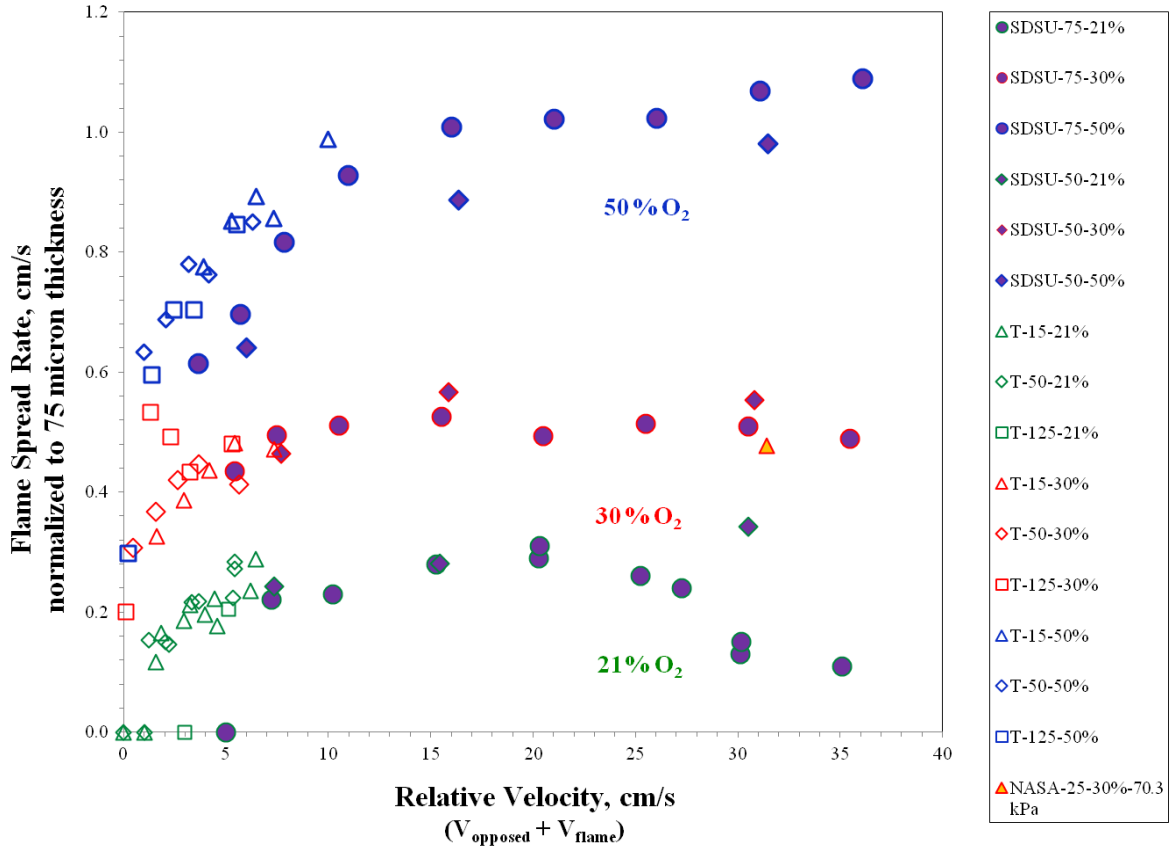


Figure 4: Flame spread rate vs. relative velocity at three oxygen concentrations. Open symbol data is from [9]. NASA data is from [5]. Legend values indicate thickness in μm - oxygen percentage by volume.



Figure 5: Flame comparison. Tests are with 75 μm PMMA at 1 atm pressure. Left: 30% O_2 concentration and 30 cm/s opposed flow velocity. Right: 21% O_2 concentration and 7 cm/s opposed flow velocity (flame is very dim blue)

3.2 Effect of Gap Height

From Figure 6 it is clear that gap height plays a large role in the flame spread rate. As the gap height is lowered buoyancy effects become less dominant and the flame begins to experience simulated microgravity conditions. While, this is sought after in a NCA, there is a point when the heat loss from the top and bottom plates will cause unrealistic spread rates. The effect gap height plays on a flame can be seen in Figure 7.

Both tests were for 75 μm PMMA at 1 atm pressure, opposed oxidizer velocity of 15 cm/s, and 21% O_2 concentration by volume. The top test was set to a total gap height of 18 mm (9 mm above and 9 mm below the sample). The bottom test was set to a total gap height of 6 mm. It is obvious that the two flames act very differently from one another, while all other conditions were the same. In the 18 mm test it is visible that the buoyancy effects are still largely acting on the flame. The flame visibly slopes upward and is bright yellow. In the 6 mm test the buoyancy effects are obviously suppressed and the flame turns much bluer. It is unclear from Figure 7, but the flame length in the flow direction also shortens greatly as seen in Figure 5.

In Figure 6 there is a noticeable difference between each gap height. At a total gap height of 6 mm the flame spread rate is greatly reduced and the maximum spread rate shifts toward a slower relative flow. As the gap height is raised the difference in flame spread rate is reduced. This is expected, since the heat loss to the top and bottom plates will be reduced as the plates are distanced from the flame. At some point the buoyancy effects will no longer grow stronger and the flame spread rate will be that of an open flame.

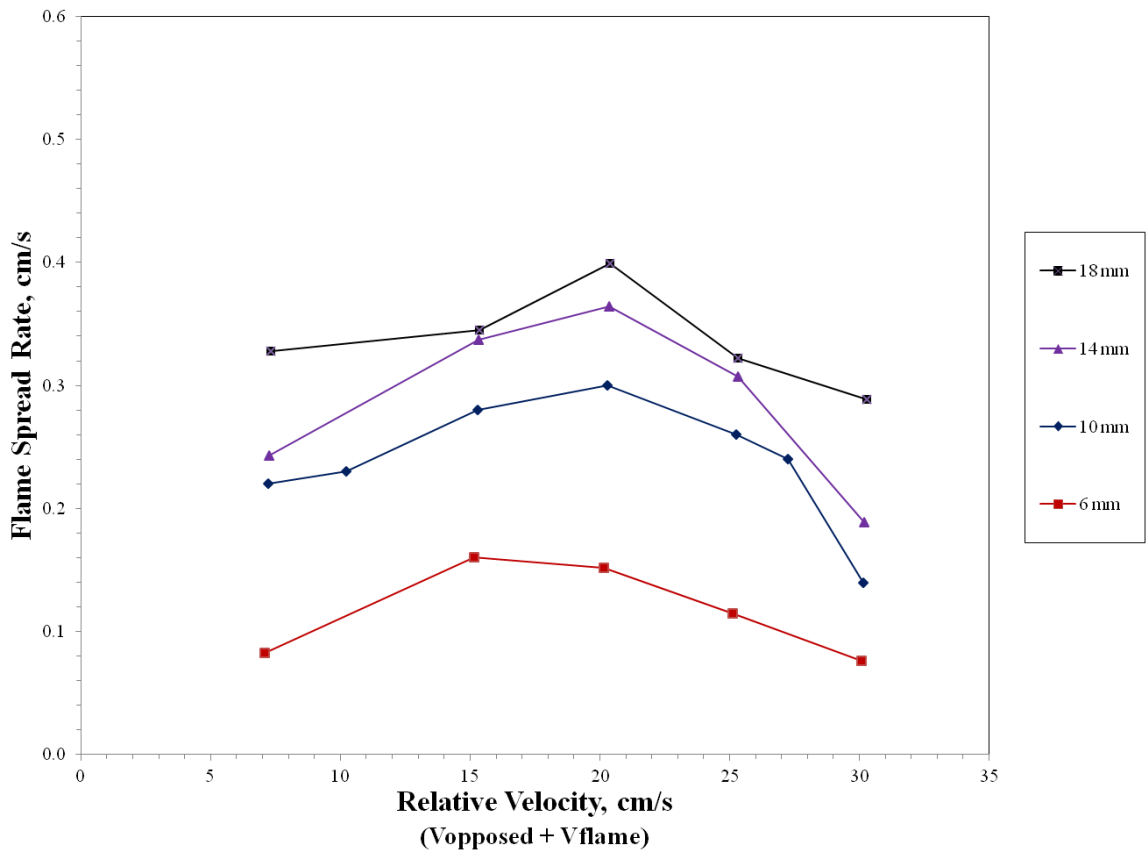


Figure 6: Flame spread rate vs. relative velocity at four gap heights.

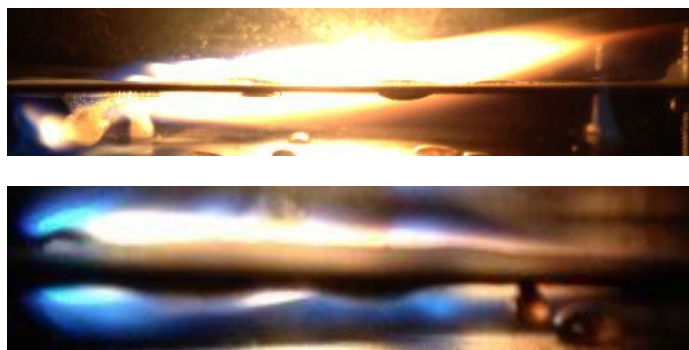


Figure 7: Side view gap height comparison (18mm-top vs. 6mm-bottom). 75 μm PMMA at 1 atm. pressure, an opposed oxidizer velocity of 15 cm/s, and 21% O_2 concentration by volume. Note that the images are not to scale.

4. Conclusions

The SDSU NCA has been shown to successfully simulate microgravity for not only thin cellulose fuels, but also for thin PMMA sheets at 1 atm pressure if the proper gap height is chosen. Tests completed in the SDSU NCA closely compare to actual microgravity conditions seen in drop tower experiments under otherwise the same conditions. These results provide further verification that the SDSU NCA is a viable option to complement or replace NASA's Test 1 for material flammability testing.

While gap height experiments have shown 18 mm and 6 mm gaps to be unfit for the SDSU NCA, it is unclear what gap height produces the best compromise in buoyancy suppression and heat loss to the top and bottom plates of the NCA. Future planned experiments will determine the best gap height for thin PMMA in the NCA.

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References

- [1] Bhattacharjee, S., West, J., and Altenkirch, R. A., 1996, "Determination of the Spread Rate in Opposed-Flow Flame Spread Over Thick Solid Fuels in the Thermal Regime.", Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, pp. 1477-1485.
- [2] R. Klimek and T. Wright, "Spotlight-16 Image Software Analysis," [Online]. Available: <http://microgravity.grc.nasa.gov/spotlight>.
- [3] D. Mulville, "Flammability, Offgassing, and Compatibility Requirements and Test Procedures" NASA-STD-6001B, 2011.
- [4] S. L. Olson, F. J. Miller, I. S. Wichman and S. Jahangirian, "Flame Spread over Thin Fuels in Actual and Simulated Microgravity Conditions," *Combustion and Flame*, vol. 156, pp. 1214-1216, 2009.
- [5] Olson, S. and Ruff, G., "Microgravity Flame Spread over Non-Charring Materials in Exploration Atmospheres: Pressure, Oxygen, and Velocity Effects on Concurrent Flame Spread," SAE Technical Paper 2009-01-2489, 2009, doi: 10.4271/2009-01-2489.

- [6] Jacob Pepper, Fletcher Miller, and Sandra Olson, "Opposed Flow Thin Fuel Flame Spread in a Narrow Channel Apparatus," Paper 12S-10, Western States Section of the Combustion Institute Spring Meeting, Arizona State University, March 19th-20th, 2012.
- [7] Jacob Pepper, Fletcher Miller, Sandra Olson, and Indrek Wichman, "A Study of the Effectiveness of a Narrow Channel Apparatus in Simulating Microgravity Flame Spread over Thin Fuels," AIAA 42nd International Conference on Environmental Systems, Paper AIAA-2012-3493, San Diego, CA, July 15th-19th, 2012.
- [8] G. W. Sidebotham, S. L. Olson, P. Rachow, F. J. Miller and I. S. Wichman, "Effect of Gap Height on Thin Fuel Opposed Flow Flame Spread in the Narrow Channel Apparatus," in *7th US National Combustion Meeting*, Georgia Institute of Technology, Atlanta, GA, 2011.
- [9] Takahashi, S., Kondou, M., Wakai, K., and Bhattacharjee, S; "Effect of Radiation Loss on Flame Spread over a Thin PMMA Sheet in Microgravity", (2002), Proceedings of the Combustion Institute, Volume 29, 2579–2586.